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Possibilities and limits in the management of mountain watersheds: Lessons from the Maya civilization

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ABSTRACT

This study focused on three pre-Columbian centres of the Maya society: Kaminaljuyu, Copan and Tikal. Historical method was used to compare their development in relation to the hydrological regime. Kaminaljuyu is based on a catchment-lake relationship, Copan on a downstream impact of a large mountain watershed, and Tikal represents an upland settlement based on a headwater spot. The main aim is to analyse water management of these centres, particularly, in view of their rise and collapse. Selected ancient Maya centres used very sophisticated water management systems with several signs of environmental and social implications. That water technology ensured their economic prosperity and consolidation of the administrative and political power for a long time. The water supply of the Maya settlement faced a serious impact of seasonal rainfall with relatively long dry periods (4–5 months) as well as fast runoff formation in the karstified bedrock. While in the Copan centre, surrounded by a large mountain watershed, the flood control was the highest priority, headwater located Kaminaljuyu and Tikal concentrated mainly on the harvest and storage of rain water. Later, these centres had to adapt to the increasing population, changing society, environment and landuse. For a long time their water management was able to adapt to the increasing demand of water and decreasing recharge of water resources. The exact reason of the collapse of these Maya centres was probably a superposition of the climate change, overexploitation of natural resources, and exceeding the carrying capacity of their environment. All those societies reached an extremely high level of hydraulic engineering, but, they were still limited in knowledge of hydrology and watershed management. Finally, it was probably a series of extreme droughts leaded to their final collapse.

1. Introduction

Watersheds in mountainous regions provide between 40 and 80% of the water resources available to lowland settlements (Messerli et al., 2004), therefore, the water resources recharge is in the focus of environmental benefits in headwater catchments (Křeček et al., 2017). FAO (2006) claimed a new generation of watershed management adopting a participatory process in the land use policy. A deep study of ancient cultures can still provide us with a valuable experience in the management of water resources and downhill impacts of mountain catchments.

The Maya civilization developed in an area that includes southeastern Mexican states (namely Campeche, Yucatán, Quintana Roo and parts of Chiapas and Tabasco), all of Guatemala and Belize, and the western portion of Honduras and El Salvador (Coe, 2011). Generally, the Maya area included both highlands and lowlands, and important foundations of the Maya culture were laid in the southern Maya highlands during the Preclassic period (ca. B.C. 2000-A.D. 250). The first Maya settlements were established along coasts and rivers, but over time the Maya has settled also the inner regions started from the southern lowlands in the Yucatán Peninsula (Lucero, 1999). The later part of the Preclassic period also saw the establishment and development of the first ancient powerful Maya city-states ruled by the divine kings (e.g. Kaminaljuyu), as well as the development of many other important features of the Maya civilization (e.g. monumental art and architecture, writing, mathematics, calendar etc.). The Preclassic period ended with a dramatic decline, which brought the abandonment of many Maya settlements.

Although many of the powerful Maya lowland centres had already been established by the end of the Preclassic period, a great flowering Maya culture was identified in the Classic period (ca. A.D. 250–900/1000). The Classic period ended again with a collapse of many powerful Maya city-states. The exact cause of this collapse seems to be multi causal, reflecting changes of the climate (more frequent droughts), increasing population and limited resources, and a crisis of the Classic kingdom. Just the collapse of the Preclassic and Classic Maya

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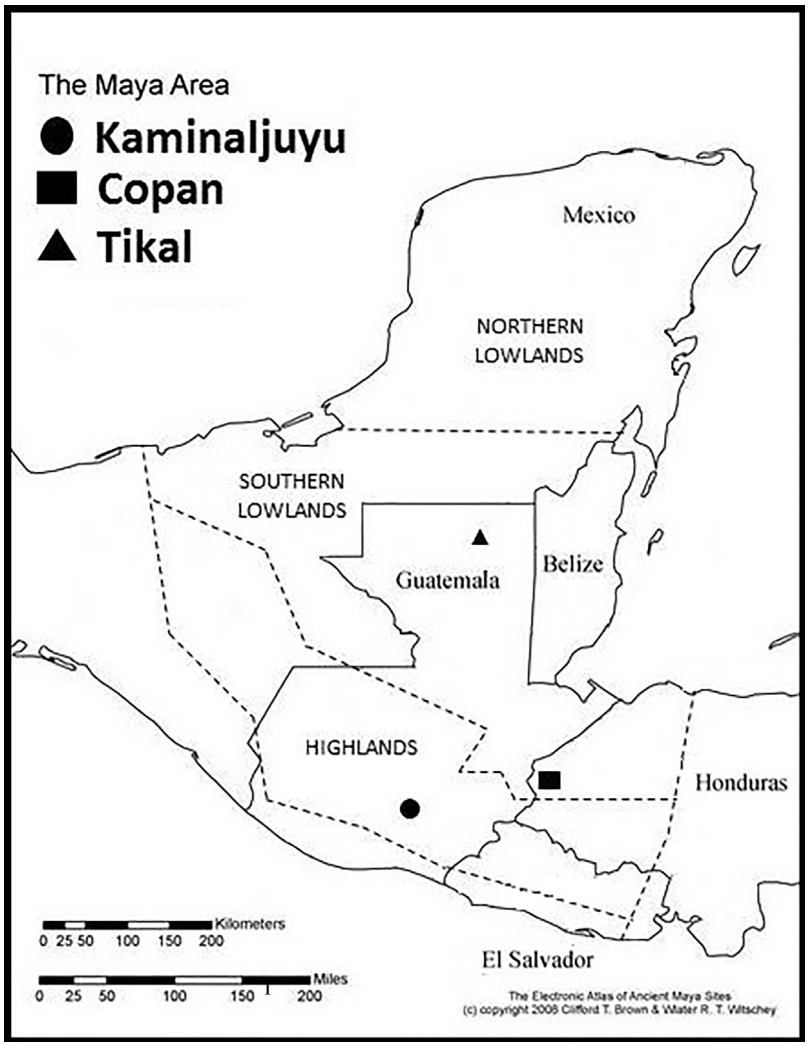

Fig. 1. Map of the Maya Area showing location of selected Maya sites and the borderline of the Highlands and Southern Lowlands (base map source: © Copyright 2001, 2002, 2005, 2008, 2009, 2010 Witschey, R. T., Brown, C. T. The Electronic Atlas of Ancient Maya Sites Updated 01/31/2010).

civilization can serve as an important example of a mismanagement of their water resources (particularly, water resources recharge).

This study focuses on the ancient Maya centres selected to represent a headwater environment and lowland-based settlements with a strong downstream impact. These three particular localities were chosen to demonstrate the ability of the pre-Columbian Maya to adapt to the different hydrological conditions. The main aim is to evaluate their water management practises and signs of the land use policy and explain impacts of water management practises and climate change on the Maya society. The experience from the ancient Maya culture can increase our contemporary knowledge on environmental and social impacts of the water management practises, as well as on the mitigation of impact of climate changes. The hypothesis is that the relatively long-term Maya civilization involved also interventions in headwater catchments as well as some signs of a participatory process in the water resource management.

2. Material and methods

Historical method was used to analyse three pre-Columbian Maya sites – Kaminaljuyu, Tikal and Copan (Fig. 1) – selected to describe diversity in hydrological conditions, related to possibilities and limits of the ancient Maya water management. The Kamimaljuyu settlement, based on a small watershed and lake system, is located in the Maya highlands; the centres of Tikal and Copan are situated in the Southern Maya lowlands. The Copan unit, located in a large valley of the semi-tropical mountains, was dependent on a large mountain watershed, while Tikal represents an upland settlement in a swampy spot. The water supply of all those units faced a seasonal rainfall distribution with relatively long (4–5 months) dry periods, and a fast runoff genesis in karstified aquifers.

Two ancient polities, Kaminaljuyu and Copan, are directly connected with a mountain catchment of a different size, the Tikal centre represents a headwater wetland. Therefore, these units can be used to analyse effects of the runoff genesis on a strategy of water management practises: mountain-related downstream water management with a water accumulation in a distant headwater spot. These social centres differ not only in their environmental conditions, but also by the date and history of their development: Kaminaljuyu was one of the most important and powerful Maya city-states during the last two stages of the Preclassic period, while Tikal and Copan reached their apogee during the Classic period. This study is based on the research on archaeology, paleoclimatology, geography, hydrology, history, epigraphy and iconography.

2.1. The study areas

The Maya civilisation extended across an area that includes southeastern Mexico, all of Guatemala and Belize, and western Honduras and El Salvador (Fig. 1). Geographically, this area consists of mountains, highlands and lowlands though Maya settlements originated mostly in the highlands.

Mayanists often divide the Maya area into three zones: the Highlands, the Southern Lowlands and the Northern Lowlands (Coe,

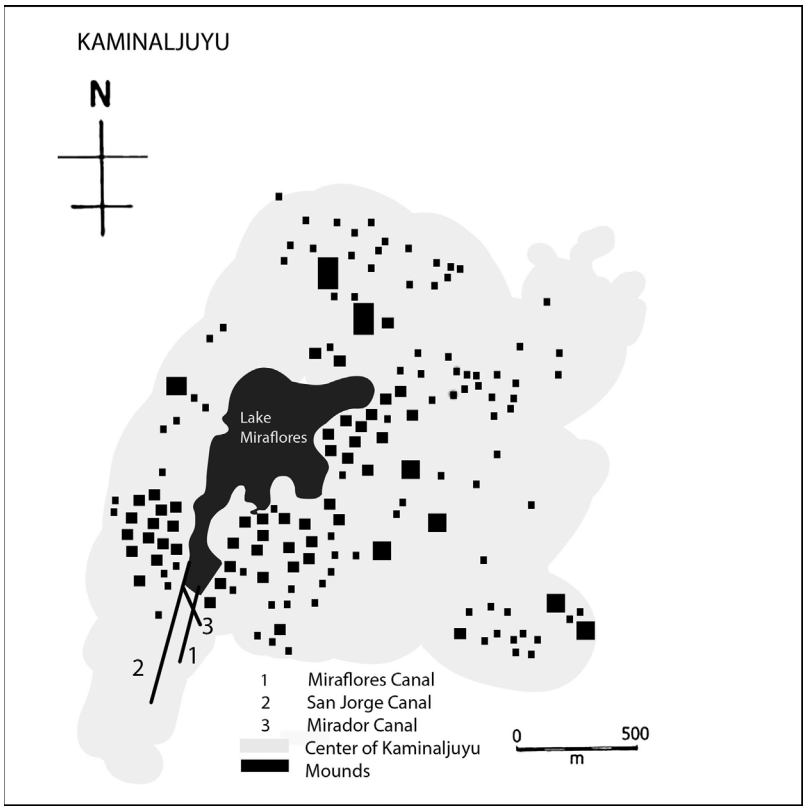

Fig. 2. The illustrative scheme of Kaminaljuyu showing the centre of the site and location of the Lake Miraflores and its canals (based on the map of Valdés, 2006).

2011). This study concentrated on two of these zones – the Highlands (the Kaminaljuyu centre), and the Southern Lowlands (the Tikal and Copan centres).

The Maya Highlands include mountainous regions of the south-eastern Chiapas, Guatemala and the western El Salvador and Honduras (Coe, 2011; McKillop 2004). The most prominent physiographical features of the local landscape are volcanic mountain ranges, both extinct and active, which form the backbone of this zone. Although many parts of the highlands are of geologically recent origin, some parts (e.g. the north part of the volcanic cordillera) are of older origin (Coe, 2011). Mountains enclose several valleys including the Valley of Guatemala, where Kaminaljuyu lies in present-day Guatemala City. As a result of volcanic activity in the Pleistocene and Holocene, soils are very rich and fertile in the Maya highlands (Wells and Mihok, 2010). According to the Köppen–Geiger climate classification system, the climate in the Maya highlands is Mesothermal, with annual rainfall between 1000 and 2000 mm, and in the sub mountain elevations between 500 and 1000 (McKillop, 2004). Precipitation shows a seasonal distribution, with a rainy season lasting from May to November (Coe, 2011; McKillop 2004). Nevertheless, unique rain conditions occur on the Caribbean hillslopes, where annual precipitation ranges from 2000 to 3000 mm (McKillop, 2004).

The Sierra Madre de Chiapas creates a drainage divide between the river systems of the Pacific and Atlantic oceans. On the Pacific side there are many streams that originate in the highlands and that are relatively short, straight and rapid. In contrast, at the Atlantic side, rivers are much larger and longer. The southern Maya lowlands are located in the southern Yuacatán Peninsula. This part of the Maya area encompasses over 68 000 km^2 and includes northern and central Guatemala, Belize, southern Campeche, north–eastern Chiapas, eastern Tabasco and western Honduras (Lucero et al., 2011; Scarborough, 1993).

The southern Maya lowlands are located in a semitropical region with noticeable wet and dry seasons. During the wet season, the annual amount rainfall varies from 1350 to 3700 mm, (Lucero et al., 2011). The rainy season is interrupted by the dry season, which usually lasts from January to May or June. Typical features of the dry season include higher temperatures and humidity. In many cases, the dry season does not show a rain at all. This fact played a key role in the headwater Maya settlements (the Tikal example) not being affected by downstream water flow from mountain catchments. These centres faced a serious seasonal lack in water, therefore, it was necessary for them to accumulate sufficient supplies of water during the previous rainy seasons. An important task for the ancient Maya was also to estimate the exact beginning of the wet season. If the Maya farmers wanted to reach a maximum productivity, they had to adopt an effective planning procedure in planting the major staples, including maize, beans and squash, immediately before the beginning of rainy seasons (Lucero et al., 2011). An underestimating this process had serious consequences in the nutrition of the Maya settlements – for example, a fungal produced aflatoxin in the maize crop stressed by the draught etc. (Normile, 2010). Therefore, predicting the exact beginning of rainy seasons was a matter of life or death for the ancient Maya civilization.

Depending on the given region, approximately 40–60% of the southern Maya lowlands are covered by *bajos* (seasonal swamps) and other wetlands (Dunning et al., 2006; Scarborough, 1993). The dominant soils of the Maya lowlands are Mollisols, which are among the most important and productive agricultural soils in the world. This study concentrated on three different types of headwater downstream effects: a catchment-lake relationship (Kaminaljuyu), downhill impacts of mountain catchments (Copan), and a headwater settlement not affected by a runoff from surrounding catchments (Tikal).

2.2. Catchment-lake relationships: the Kaminaljuyu unit

The ancient Kaminaluyu unit is an example of a municipal centre dependent on water runoff genesis in a small headwater catchment. The Kaminaljuyu settlement located in the broad and fertile plain of the Valley of Guatemala (in the elevation of 1,530 m) was one of the most important Maya centres of the Preclassic period. Its significance during

the Middle Preclassic period (B.C. 900 − 400) and the following Late Preclassic period (B.C. 400- A.D. 250) is undeniable. The site extended over an area of 5 km^2 around the Lake Miraflores (Sharer and Traxler, 2006; Emery et al., 2013), Fig. 2. The Valley of Guatemala is enclosed by hills of the southern Sierra Madre Mountains (about 2000 metres high) on the divide between the Pacific and Atlantic watersheds (Helms, 1982). Sharer and Traxler (2006) identified the Valley of Guatemala as the largest and most fertile basin in the Maya highlands. Soils in that valley are volcanically enriched, useful for an agriculture development. Nevertheless, the surrounding steep slopes and ravines are vulnerable to soil erosion, particularly, by a shift from the natural vegetation to a crop production. The climate is temperate with a seasonal distribution of precipitation: more than 90% of rainfall occurs during May–December (Emery et al., 2013). In the Preclassic period, many smaller lakes were noted in depressions of the Guatemala Valley, the Lake Miraflores belonged to the larger lakes on this area (Popenoe de Hatch et al., 2002).

The depression of the Lake Miraflores was of a tectonic origin, filled by rain water and several small karst springs (Popenoe de Hatch et al., 2002). Those springs drained a watershed area of approx. 20–30 km^2. The surface of the lake achieved 25 ha and the depth of 3.15 m (Love, 2016; Popenoe de Hatch et al., 2002) served as the main source of the Kaminaljuyu water supply – both the municipality and an irrigation of the agricultural fields (Rice, 2007; Valdés 2006). Such a relatively shallow lake was very sensitive to sedimentation and eutrophication. According to the archaeological excavations, this lake completely dried up around A.D. 100, and the Kaminaljuyu centre has declined (Popenoe de Hatch et al., 2002).

2.3. Downhill impacts of mountain watersheds: the Copan unit

The Copan centre has developed in the fertile Copan Valley situated in the semitropical mountains of western Honduras (Fash and Davis-Salazar, 2006; Glass, 1966). This municipality extended in elevations between 550 and 700 m, being affected by the large mountainous watershed of 530 km^2 with the highest elevation in 1,890 m (Fig. 3). Mayanists classify Copan among the southern Maya lowland centres, based on its original culture (Sharer and Traxler, 2006). The major soils in the Copan Valley are Inceptisols (covering around 84% of the area) of rather low fertility, while the rest of the valley is covered by more

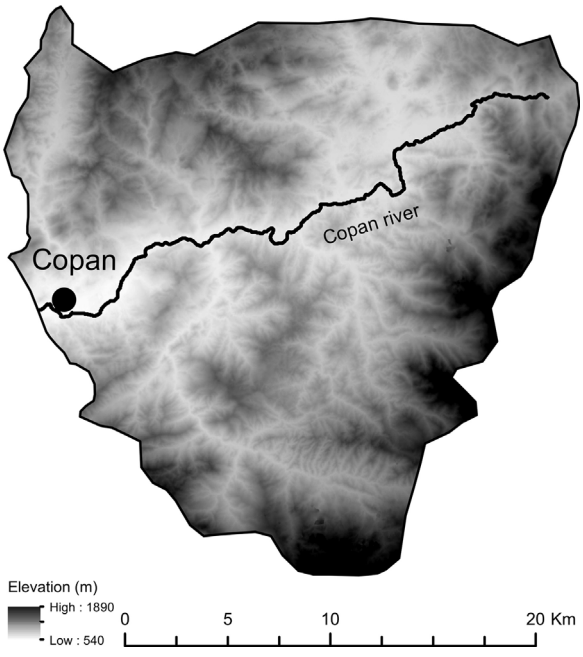

Fig. 3. Map of the Copan centre and its watershed (source: JAXA).

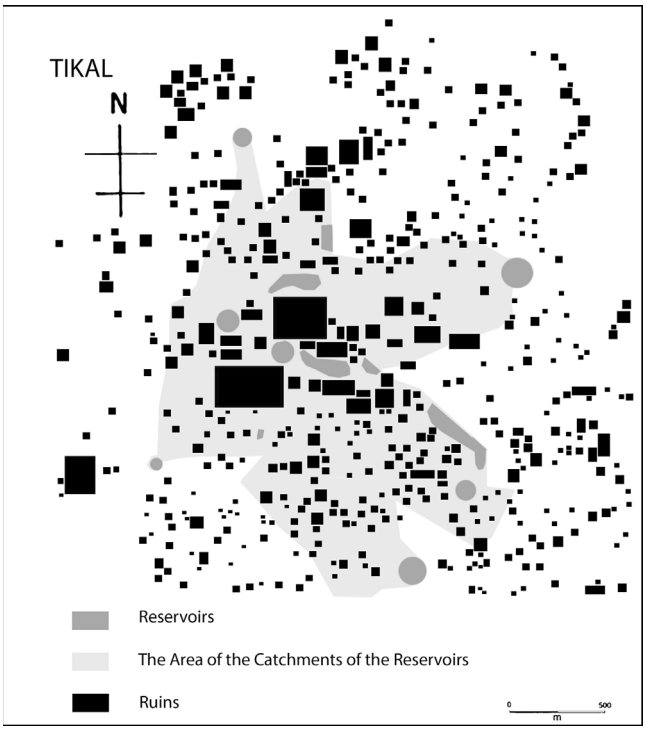

Fig. 4. The illustrative scheme of Tikal showing the centre of the site and its main karstified springs and small water reservoirs with their area of the catchments (based on the map of Scarborough et al., 2012).

fertile Entisols and Mollisols (Wingard, 2016). Fash and Davis-Salazar (2006) described the Copan unit with the mean annual rainfall of 1700 mm as a water-rich environment (a culture of rain). The valley is drained by the Copan River with many tributaries and springs originated at the foot of the mountains (Fash and Davis-Salazar, 2006).

2.4. Headwater settlements: the Tikal unit

The Tikal settlement is located at the heart of the Petén department in northern Guatemala and was one of the most powerful Maya kingdoms in the Classic period. This great ancient Maya city lies just on the border between the drainage system of the Belize River and the Usumacinta River (Glassman and Anaya, 2011; INSIVUMEH, 2015). According to UNESCO maps of groundwater regions, Tikal belongs to the Caribbean islands and coastal plains of North and Central America, with an annual recharge of groundwater resources 50–100 milimetres (UNESCO-IHP, 2009).

Tikal (Fig. 4) is among the largest Classic Maya sites, with residential area covering about 16 square kilometres (Coe, 2011), extending over a karst region, composed of carbonate rocks from the Mesozoic and Cenozoic Era, which rises above swampy lowlands (Sharer and Traxler, 2006; Dunning et al., 2015). Because of a remarkable internal drainage system of this highly karstificated spot, the groundwater table occurs in approx. 180 m below the surface (Dunning et al., 2015; Lucero et al., 2011). In the Tikal area, mainly Mollisols, Vertisols, Inceptisols and Entisols soils were identified and mapped (Olson, 1981). While Vertisols located in *bajos*, were unsuitable for heavy buildings, Mollisols represented ideal building conditions, but, on the other hand, Mollisols at the Tikal site were vulnerable to soil erosion (Olson, 1981).

3. Results and discussion

3.1. Preclassic and classic Maya water management

3.1.1. The Kaminaljuyu catchment-lake relationship

The Kaminaljuyu settlement was based on the water supply from the Miraflores lake filled by surrounding mountain watersheds. The archaeological research discovered three enormous channels connected to the Lake Miraflores, which were used to feed large irrigation systems (Valdés, 2006). The oldest channel (Miraflores Canal) originated already in the Middle Preclassic period (B.C. 900 − 400), and the other two (San Jorge Canal and Mirador Canal) were built in the Late Preclassic period (B.C. 400- A.D. 250). The Miraflores Canal (1 kilometre long) was located in the south of Kaminaljuyu. Designed to transfer a high amount of discharge (V-shaped cross section, 3.3 m wide and 5.8 m deep), this channel served also to control floods (Valdés, 2006). The banks of the channel had variable heights, respecting the natural inundation scheme, demonstrating a relatively high technical level of the Kaminaljuyu centre. In the beginning of the Late Preclassic period, this channel was converted to a trash pit, probably, because of sedimentation and increasing flood events according to the changing climate (Fig. 5). This fact corresponds with results of Knox (2003) identifying more frequent floods in the period 500-200 BCE. Instead, the almost parallel canal of San Jorge with three times the capacity (8 m deep) was build there. Valdés (2006) considered the San Jorge Canal as a river with several branches located in surrounding agricultural fields. However, Popenoe de Hatch et al. (2002) suggested that the new channel was constructed deeper below the terrain because of a decreasing water level in the Miraflores lake. That decreasing water level in the lake probably reflected the rising exploitation of water in Kaminaljuyu.

The additional Mirador Canal was smaller, 2.6 m wide, 3 m deep and 230 m long. Valdés (2006) noted a relatively high technology of this construction being able to control the discharge, which means more effective exploitation of the lake water. The important task of all these channels was to irrigate the agricultural fields. Valdés (2006) estimates several hundreds of farmers working in the surrounding 5 km of fields in the Late Preclassic period. Main crops were maize, legumes and squash. Late excavations identified several large-scale cooking spots serving as communal kitchens for the field workers (Valdés, 2006; Popenoe de Hatch et al., 2002).

For the domestic water supply, a system of small water reservoirs pointed in karst holes (approx. 6 m in diameter) was discovered in the southern section of Kaminaljuyu (Valdés, 2006). These reservoirs captured rainwater and runoff harvested by surrounding slopes of the terrain. Investigations of the north-eastern part of Kaminaljuyu discovered another Y-shaped canal (1 m wide and 0.65 m deep) associated with a Late Preclassic monumental construction – a pyramid 16 m high located at the west side of the Acropolis complex of Kaminaljuyu (Valdés, 2006). Additionally, an aqueduct of the Late Preclassic period (4.5 km long and 15 m high) was constructed to conduct water from the mountains of the southeast part of the Guatemala Valley to the vicinity of Kaminaljuyu.

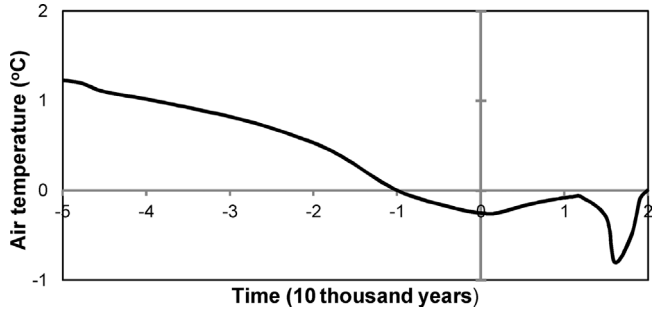

Fig. 5. Fluctuations in air temperature during the last seven thousand years (from 5,000 BCE to 2,000 CE), an average figure for the entire globe based on the data of File (1991).

Building such an extended water supply and irrigation systems required a certain level of the political and social organization. The construction of canals and communal kitchens is an evidence of the rising power of ruling elites, being able to order and organize these public projects. Beside the irrigation canals, many monumental structures and sculptures in Kaminaljuyu were built to glorify the rulership (Rice, 2007). The irrigation system that led to an increasing agricultural activity initiated a movement of people to Kaminaljuyu and rising its population, also supported the power of the rulers (Sharer and Traxler, 2006). Therefore, the system of water management ensured the economic prosperity of the Kaminaljuyu city as well as a consolidation of the administrative and political power. From a remarkable decline in pottery (both in the number of types and the quality of manufacture), it is evident that by the end of the Preclassic period, the Kaminaljuvu centre was under an economic and sociopolitical tension (Popenoe de Hatch et al., 2002).

The Miraflores lake first of all served as an important source of food – particularly, fish, turtles, molluscs and water-fowls (Emery et al., 2013). Moreover, the analysis of remaining animals shows changes in the lake ecosystem: whereas the remains of the first part of the Late Preclassic period included a high proportion of freshwater fishes (e.g. cichlids indicating the well-oxygenated water), and waterbirds preferring open shorelines, the remains of the end of the Late Preclassic period revealed gar, a fish which can adapt to conditions of low oxygen, and quail, an open habitat bird (Emery et al., 2013). The gar population could indicate a decline of waters in the canals affected by sedimentation and probably overpopulated by algae (Emery et al., 2013). Emery et al. (2013) highlighted that these findings support the theory of a gradual drying of this area and a desiccation of the Lake Miraflores. The great Lake Miraflores had dried up around A.D. 100, and the sophisticated San Jorge and Miraflores canal system was no longer operational. Whether the exact cause of desiccation of Lake Miraflores was climate change, overexploitation of the lake due to irrigation canals, or seismic shifting is still unknown (Emery et al., 2013). However, what is certain is that around the time when the lake disappeared, Kaminaljuyu went into decline.

All these findings support the hypothesis, that Kaminaljuyu likely owes its success to its water system (Scarborough, 2006). Although there might have been additional factors that led to the political and economic domination of Kaminaljuyu in the Maya highlands during the last parts of the Preclassic period (such as its strategic location on the route between the Pacific coast, Caribbean and interior), the presence of Lake Miraflores and the complex irrigation system was undoubtedly one of the most important. Building the irrigation system led to the intensification of agriculture and this resulted in further population growth and wealth, and helped to centralize the political power of Maya rulers (Sharer and Traxler, 2006). When the lake dried up, Kaminaljuyu lost its status of the dominant centre in the Maya highlands.

3.1.2. The Copan downstream impacts

The water management was different in Copan, affected by downhill impacts of a mountain watershed. Located along the Copan River with a permanent discharge and concentrated alluvium, the Copan municipality exploited a perennial source of water from the river. In addition, there were identified five smaller seasonal tributaries of an intermittent hydrological regime (Davis-Salazar, 2006) originating in the surrounding mountains and flowing through the Copan Valley before joining the Copan River. Undoubtedly, the meandering Copan River with its tributaries played an important role in the life of the Copan centre. The Copan site was occupied from the Early Preclassic to the Postclassic period. During that time, the Copan Valley faced frequent periods of aggradation and lateral movements of the river channel, and also widening the inundation plain (Hall and Viel, 2004). The majority of the ancient Maya inhabitants of Copan lived in the

"urban core", located on the alluvial terrace, which includes the civic-ceremonial centre of Copan and the surrounding residential areas (Davis-Salazar, 2006). Therefore, the core of the Copan settlement showed a high building density (approx. 1400 structures per square kilometre) while in the hinterland only approx. 100 structures per square kilometre (Lucero, 2006). The archaeological research has revealed that ancient inhabitants of Copan were very knowledgeable in the hydraulic technology that helped them to control the river and to deal with the undesirable effects of an active river system (Hall and Viel, 2004; Fash and Davis-Salazar, 2006; Davis-Salazar, 2006). This technology included an urban-drainage (and flood-control) system that consists of substructure and subterranean conduits, stucco channels and plazas, roof drains, splashboards, and causeways (Davis-Salazar, 2006).

The stucco channels differed from foregoing conduits not only in material, but also in their function − their material was easier to be added, modified, or removed, and, therefore, they were used in case of immediate drainage and erosion problems (Davis-Salazar, 2006). The role of stucco and stone plazas, and patios in the drainage systems is well known also from other May sites: their surface was slightly sloped to a direct water runoff by substructure conduits (Davis-Salazar, 2006). The effectiveness of roof drains was enhanced by splashboards – slabs of limestone – that helped to reduce erosion caused by the runoff from roof drains.

These water-control features were used in the Late Classic period (A.D. 600–800). Building such an urban-drainage/flood-control system may have been a way how the ancient inhabitants of Copan responded to changing climate and environmental conditions. As a recent research has confirmed, whereas the Early Classic period (250 CE-600) is characterized by dry conditions, the Late Classic period indicates substantially wetter conditions in the southern Maya lowlands (Douglas et al., 2015). Therefore, the flood control (including flood prevention) was one of the highest priorities for a sustainable existence of the Copan settlement.

Even a permanent flow in the Copan River observed year-round, the discharge was highly variable with a season. Therefore, Copan used also several artificial reservoirs. Moreover, water in the river became undrinkable during the rainy seasons, being contaminated namely by muddy silt (Lucero, 2006; Fash and Davis-Salazar, 2006; Darley, 2011). These artificial water reservoirs strongly supported the political power of the ruling elite (Fash and Davis-Salazar, 2006; Lucero, 2006). The power of rulers was also emphasized by several water related rituals. The importance of water can be demonstrated by the name of the Copan's Ruler 12–written K'AHK'-(U-)TI'-WATER·SERPENT-K'AWIIL (Stuart, 2007). The Water Serpent is a well-known character from Maya iconography, where this watery creature is typically depicted as a jawless snake with downward-curving bird beak and a complicated headdress that very often includes a water lily and a fish or two (Coltman, 2015; Stuart, 2007). Although the Water Serpent is still poorly understood, there is some information that may point to the importance of water-connected rites in Classic Maya society. As Stuart (2007) points out, the most frequent context in which the Water Serpent occurs on sculpture is connected with ritual costumes, which Maya kings or nobles wore during Period Ending rites. This discovery could be particularly significant, because these ceremonies, which were connected with the endings of some period of the complex Maya calendar, were very important for the ancient Maya. Not only did Classic Maya rulers erect stelae to commemorate these special events, but they also often built opulent pyramid complexes or rebuilt older ones. Stuart (2007) also argues, that the Water Serpent may be an ancient Maya manifestation of varied aquatic spirits and that the snake itself can be seen as "animate water," which emphasizes meandering streams and rivers. As in the case of other Maya gods, The Water Serpent also encompasses many characteristics and functions and is connected with complex symbolism, but the embodiment of animate and active terrestrial waters, such as rivers, springs, lakes, pools and cenotes, could be the most important of all (Coltman, 2015). According to Nehammer Knub et al. (2009) the Water Serpent is probably the second-most impersonated deity in the corpus of Maya hieroglyphs, second only to the Maize God. Deity impersonations were among the most important rites of the Classic Maya rulers, and therefore impersonation of the Water Serpent shows us the key role that this embodiment of water played in the Classic Maya religion and rituals.

Nevertheless, as well as many other Classis Maya centres during the Terminal Classic period (800–900/1000C.E.), Copan also went into decline that ended in a collapse. As mentioned earlier, the exact cause of the collapse remains the subject of debate and it is generally believed that it was reason of several factors. In the case of Copan, droughts probably were the main cause in the Classic collapse. The evidence of sediments in the Copan Valley supports this fact: McNeil et al. (2010) reported the evidence of extremely low water levels in the river, or even a completely dry channel.

3.1.3. The Tikal headwater management

The Tikal settlement was another of the most important and powerful kingdoms in the ancient Maya. Its initial colonization can be traced back to B.C. 700. Tikal reached its apogee during the Late Classic period (Dunning et al., 2015). For a long time, researchers have been fascinated by the question how the city was able to maintain its substantial population and become so successful in spite of its location in an upland swampy area without a major perennial stream or lake (Lentz et al., 2014; Lentz et al., 2015). The key was in a very effective water management, using probably one of the most sophisticated hydraulic systems in the New World (Sheets, 2015; Scarborough, 1993; Scarborough and Gallopin, 1991).

For many years, Tikal has been viewed as a completely rainfall dependent city. However, as a recent research has revealed, there were ancient karstified springs that spurred early colonization of the site (Scarborough et al., 2012). Nevertheless, these springs fell victim to architecture and to a population boom during the Classic period. Scarborough et al. (2012) highlighted a reservoir system available to the growing population, therefore, gradually, Tikal became dependent on the development of small water reservoirs. This dependence might have been not only the result of the slow recharge of the natural streams (which had disappeared around the beginning of the Early Classic period) and the growing demand for water, but also the result of a drought that, as paleoclimatological research has revealed, may have affected Maya lowlands at the end of the Late Preclassic period (Scarborough and Grazioso Sierra, 2015). Already in the Early Classic period, there was an evidence of the loss of several springs and a development of new reservoir construction, as a reaction on a landscape changes. However Tikal's water management was not in full flower until the Late Classic period.

Scarborough and Grazioso Sierra (2015) highlighted that the water resource system of the Late Classic Tikal consisted of several interdependent landscape components that were highly associated with harvesting the rainwater in wet seasons. This system can be divided in three groups according to the type of reservoirs – 1) large summit-ridge reservoirs, 2) bajo-margin tanks, and 3) small residential reservoirs. These components worked together in a "water management system" providing Tikal with a sustainable water supply year around. The central part of Tikal had six sizeable summit-ridge reservoirs built by damming streams and formed by positioning of series of causeways and dams, downwards excavation and expansion in width (Scarborough and Grazioso Sierra, 2015). As an earlier research has revealed, catchment area of these reservoirs, which drained this human-modified watershed, range from 9 to 62 ha, and the runoff from these surfaces was sufficient to fill the reservoirs. The summit-ridge reservoirs alone contained from 105 to 244 thousand cubic metres of water (Scarborough and Grazioso Sierra, 2015) and their catchments could collected more than 900 thousand cubic metres of water based on 1500 mm of annual rainfall (Lucero et al., 2011). These estimates indicate that these Tikal's reservoirs could easily have provided water for 50,000 people

(Scarborough and Grazioso Sierra, 2015). The recent research has also revealed that the Tikal Maya used sand filtration to clean the water entering reservoirs, and a switching station that facilitated seasonal filling and release, sluices, system of dams, and canal segments (Scarborough et al., 2012; Scarborough and Grazioso Sierra, 2015).

Therefore, the Classic Tikal water management can serve as a very good example of a successful adaptation to changing environmental conditions. Despite of more serious droughts registered in the beginning of the Early Classic period, Tikal was still able to survive and build very sophisticated water management systems that enabled Tikal to provide sufficient water for its growing population, which reached its peak during the Late Classic period, and to become one of the largest and most powerful polity in history of the Maya civilization.

Nevertheless, not even the Tikal sophisticated water management was able to cope with extreme droughts that occured in the Terminal Classic period (A.D. 800–900/1000), Douglas et al. (2015). Beach et al. (2016) claimed that such a drought would have been challenging to any civilization, and especially so for the Maya living in an area without perennial water sources. Although the Classic collapse of Tikal was probably multi-causual, the series of droughts were most likely one of the main cause of Tikal's decline during the Terminal Classic period. For a long time, the Maya units have been adopted several measures to sustain the rising civilization pressure and environmental changes, similar with the GAIA Daisyworld model (Lovelock, 1995) finishing with a critical threshold.

3.2. Impacts of deforestation and other human interventions

Based on the analysis of animal remains at Kaminaljuyu, Emery et al. (2013) showed that at this area forests retreated dramatically during the time of its existence: various open-habitat species and the deer (preferring disturbed and agricultural landscapes) became more common in the later periods. Such a forest retreat might be attributed either to expanding settlements and agriculture, or to a changing climate and lacustrine conditions (Emery et al., 2013). The question arises whether the ancient Maya understood the rainfall-runoff relationship in a catchment scale, and whether they fully understood how human activities affected the landscape and their environment. In the case of Preclassic Kamninaljuyu, its inhabitants may have not fully understood the impact of deforestation, because in spite of the gradual process of the lake drying up and a retreating of the forests, there was still great development (construction projects) during the last time of the Late Preclassic period in Kaminaljuyu, when a number of structures (e.g. earthen pyramidal platforms and associated lower structures) were built (Sharer and Traxler, 2006). Most of these structures used timber, mud plaster and thatch, and were located on the adobe-plastered platforms (Sharer and Traxler, 2006). Lake Miraflores showed signs of drying up with a loss in catchment forest cover, indicating an over-exploitation of natural resources (namely water and timber).

A different situation was found in the Classic Copan centre. For many years, Copan had been held up as a cautionary example of environmental degradation as a product of man-made and large-scale deforestation. Mayanist believed that the deforestation was one of the main causes of the Copan collapse. However, McNeil et al. (2010) claims that despite a rising population and shrinking land base during A.D. 600–900, the Copan Maya were still skilled landscape managers. Based on the analysis of a long sediment core, it was shown that the forest cover increased in Copan particularly in A.D. 400–900, culminating in A.D. 900 (McNeil et al., 2010). Thus, the most dramatic deforestation in Copan during the last 3000 years was identified around B.C. 900, which likely corresponds to the widespread shift to an agricultural landscape. In this case, disappearing forests may have been an important stimulus leading the Copan Maya to a better understanding of impacts of human activities on the environment, and to a better protection of the surrounding environment. Whereas the Early Classic period saw a great episode of intense construction activity in Copan which would have required large amounts of woods to produce stucco for the structures and plaza floors, the Late Classic period buildings are distinguished by thinner layers of stucco on sculptured buildings (McNeil et al., 2010). Because the production of stucco requires large volumes of wood, the reduction in the timber exploitation may have been one of available conservation methods to control natural resources. Later, still some evidence supported this hypothesis, for example an increase in *Pinus* and other arboreal pollen grains that indicate that the Late Classic Mayas were practicing some signs of the environmentally sound landscape management than they had during the Early Classic period, possibly in response to the soil depletion caused by deforestation and erosion in the Preclassic and Early Classic periods (McNeil et al., 2010). It seems to be evident that the Classic Maya of Copan may have learnt from their previous mismanagements.

The recent research has revealed that the Late Classic Maya at Tikal practiced intensive forms of agriculture (including irrigation, terrace construction, arboriculture, household gardens, and short fallow swidden) coupled with carefully controlled agroforestry and a complex system of water retention and redistribution (Lentz et al., 2014). Regarding agroforestry, it should be mentioned that populations of Tikal required a huge amount of wood, and the largest part was firewood needed for cooking. Lentz et al. (2014) estimated wood quantities required annually at Tikal for fuel and constructions as 42 000 t (approximately equal to the amount of wood available on a sustainable basis – 39 000 t per year) from the Tikal upland and bajo forests. Nevertheless, the Tikal Maya developed a sophisticated system of agroforestry, they favoured the productive trees and, during their early centuries, avoided deforestation (Sheets, 2015). The area of resource

Unit	Time of existence	Main water resources	Water management priorities	Main components of the water management system	Main reasons of fall
Kaminaljuyu	cca BC 1200 -900+ AD*	Lake system	Lake protection and irrigation	**irrigation channels**, sub-reservoirs, aqueducts	Climate change, overexploitation of the lake and exceeding the carrying capacity of the environment
Copan	cca BC 1000 - 900/1000 AD	River channel	Flood control and water storage	**substructure and subterranean conduits**, stucco channels, plazas, roof drains, splashboards, causeways, reservoirs	Extreme droughts and changing discharge frequency
Tikal	cca 700 BC - 1000/11000 AD	Karstified rock	Rain water harvest	**reservoirs**, sand filtration, switching station facilitating seasonal filling and release, sluices, system of dams, canal segments	Extreme droughts and insufficient water resources recharge

Fig. 6. Table showing the comparisons between the three case studies. * Time of existence shows the beginnings of settlements in the localities and their final abandonment. Kaminaljuyu was reoccupied in the Classic period after its decline around A.D. 100 when the Lake Miraflores completely dried up. However, Kaminaljuyu never regained its position as one of the most important Maya city-states.

extraction around Tikal was approx. 1100 square kilometres (Lentz et al., 2014), including necessary food, fuel, and timber. The system of agroforestry had worked until around A.D. 600, when Tikal's population exceed the carrying capacity of the environment (Sheets, 2015).

4. Conclusions

The selected ancient Maya centres used very sophisticated water management with several signs of environmental and social implications. That water technology ensured their economic prosperity and consolidation of the administrative and political power for long periods. The water supply of the Maya settlement faced a serious impact of seasonal rainfall with relatively long dry periods (4–5 months) as well as fast runoff formation in the karstified bedrock. The studied water management strategies differ according to different hydrological conditions including a small headwater area, catchment − lake relationship, and downstream impacts of a large catchment. While in the Copan centre with a large mountain watershed the flood control was the highest priority, in headwater conditions of Kaminaljuyu and Tikal it was mainly the harvest and storage of rain water (Fig. 6).

In their history, all the focused Maya centres faced changes: increasing population, changing landscape, environment and society. For a long time their water management was able to adapt to an increasing demand of water and changes in the water resource recharge. The exact reason of the collapse of Maya centres was probably a superposition of the climate change, overexploitation of natural resources, and exceeding the carrying capacity of their environment. All those societies reached an extremely high level of hydraulic engineering, and organization of big public water supply projects with signs of participatory programmes. However, they were still limited in knowledge of hydrology and watershed management. Finally, it was probably a series of extreme droughts which was the main cause of the collapse of these ancient Maya units, confirming the *Gaia theory* of a threshold in the climate change.

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